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STUDY OF ELECTRONIC TRANSPORT AND BREAKDOWN IN THIN INSULATING FILMS

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13. ABSTRACT

Progress is reported in the study of high-field electronic transport and dielectric breakdown in technologically important thin insulating films on Si, namely SiO_2, Al_2O_3, Si_3N_4, and their layered composites.

Corona charging in a controlled gaseous ambient has been developed as a precise, nondestructive tool for the study of high-field phenomena in thin insulating films. Exceptionally clear-cut and reproducible results have been obtained on thermally grown SiO_2, and the study is being extended to other insulators and is being combined with vacuum UV techniques.

The breakdown of SiO_2 and Al_2O_3 films is being studied also by the self-quenching technique. Striking differences in the time scales of breakdown and in the topographical features of the breakdown region are observed in SiO_2 among the four combinations of substrate type and polarity of surface potential.

The generation of deep traps in insulating films by ion implantation and by electron-beam irradiation is under study.

The scanning electron microscope is being used to study lateral nonuniformities in the insulator and at the insulator-semiconductor interface. A theoretical and experimental study of MIS techniques for characterizing lateral nonuniformities is also under way.

Monte Carlo calculations have been made of hot-electron distributions in insulating films. A theoretical study has been directed toward identification of the physical mechanisms involved in localized breakdown in thin insulating films.

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Theory of insulator breakdown						

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I. INTRODUCTION

This report reviews progress in a comprehensive research program directed toward a basic understanding of electronic transport, charge trapping, and dielectric breakdown in the thin insulating films used in integrated circuits. The films being studied are silicon dioxide, aluminum oxide, silicon nitride, and their layered composites, on silicon substrates. The purpose of the program is to provide a correct and quantitatively accurate understanding of the physical processes leading to breakdown of the films, with the ultimate objective of providing a rational basis for the choice of materials, processing methods and treatment of insulating films for increased yield in manufacturing and greater reliability in use. The program includes both experimental and analytical aspects, as follows:

(1) Corona-Induced Nondestructive Breakdown of Insulating Films

The use of a corona discharge in a gas at atmospheric pressure to contact the unmetallized surface of an insulating film provides a means of inducing charge transport across the insulating film, and the virtual absence of lateral surface conduction allows the use of very high field intensities - tantamount to breakdown - without destruction of the films. We have developed the corona-charging technique together with auxiliary new techniques such as the use of the charge-separating property of a PN junction to identify the principal charge carrier in the insulator and the use of a comparison method for measuring the steady-state surface potential of the insulator during charging, and have applied these to a study of charge injection, transport, and trapping in SiO_2 films on Si. In support of the experimental work, a theoretical study has been made of the tunneling of electrons into the insulator from the thin potential well formed in the semiconductor by strong band bending under high-field conditions.

(2) Self-Quenched Breakdown of Insulating Films

In this study we use a very thin metallization of the insulator to achieve local removal of the field-plate material at the site of a local breakdown; thus the breakdown, although locally destructive, is

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self-quenching. This program includes an investigation of the time evolution of the breakdown, the effect of previous surface damage, and optical microscope and scanning electron microscope (SEM) studies of local breakdown damage.

(3) Charge-Discharge Studies of Charge-Carrier Trapping in Insulating Films

Trapping centers in the films are probed by charge-discharge techniques. Internal photoinjection provides carriers to charge the traps and heat or photon energy is used to stimulate discharge of trapped carriers.

(4) Charge Injection by Electron Beam

In this study, electron injection into the insulator is achieved by use of a low-energy nonpenetrating beam. This technique is combined with charge-discharge studies to probe trapping centers in the films.

(5) Scanning Electron Microscope Studies

The scanning electron microscope (SEM) is used to probe the insulating film and the insulator-semiconductor interface both before and after breakdown of the film. The signal channels employed for imaging in the SEM are primary and secondary scattered electrons, beam-induced current in the sample, and beam-induced X-rays and Auger electrons for compositional characterization. The relation between the effects of nonuniformities in stored charge or impurity aggregation in the insulator or at the interfaces, and structural defects leading to breakdown is being studied.

(6) Study of Lateral Nonuniformities in MIS Structures

In this companion effort, funded from other sources, we are studying Metal-Insulator-Semiconductor (MIS) measurement techniques for the detection and characterization of lateral nonuniformities in thin insulating films.

(7) Monte-Carlo Calculations of Hot-Electron Distributions

Monte-Carlo calculations have been made of hot-electron distributions produced by high electric fields in insulating films. Recent emphasis has been on the runaway process induced by an energy-

dependent mean free path.

(8) Theoretical Modeling of Local Breakdown

A theoretical study has been directed toward identification of the physical mechanisms critical to localized electrical breakdown in thin insulating films.

II. REVIEW OF PROGRESS

Significant progress has been made in all of the abovementioned areas, and reports and papers describing the results are in various stages of preparation, as described below.

(1) Corona-Induced Nondestructive Breakdown of Insulating Films
(Z. A. Weinberg, H. S. Lee and H. H. Chao collaborating)

The use of ions produced in a corona discharge[1] to charge the surface of an insulating film is well known in the electrophotographic industry.[2,3] Williams and Willis have used corona charging as a research tool to study electron multiplication and surface charge on ZnO crystals.[4] This method was also used by Williams and Woods[5] to obtain current-voltage characteristics of thin films of SiO_2 thermally grown on silicon, but their experiments were performed in the open air with the resulting possibility of surface contamination, and their lack of a method of measuring surface potential during charging made it necessary for them to confine their measurements to the discharge condition that ensued after the sample had been removed from the corona.

The use of a corona discharge to contact the exposed, unmetallized surface of a thin insulating film has several important advantages over alternative methods. First, the ions in a corona at atmospheric pressure have a very short mean free path and strike the surface at only approximately thermal energy; hence they do not produce the undesirable secondary excitations that result from the impact of more energetic ions. Second, the distribution of ionic current is determined essentially by the electrostatic field configuration, and so the corona acts as a current source for each element of area of the insulator surface. Third, if the humidity is kept low, the lateral surface conductivity of the insulator is negligible.

Unlike a metallized sample, where the electrostatic energy of the entire structure can discharge through a localized breakdown and cause destruction of the sample, a corona-contacted structure is comparatively insensitive to the presence of weak spots. Extremely high field intensities and steady-state currents tantamount to breakdown can be maintained without destruction of the films.

We have developed corona charging into a more precise tool for studying the transport and breakdown properties of thin insulating films. Toward this end we have arranged a suitable environmental chamber so that the measurements can be made in a controlled gaseous ambient,[6] and we have devised a comparison method for measurement of the surface potential of the insulator during charging,[7] thus making steady-state measurements possible. We have also developed a p-n junction technique for determination of the sign of the dominant current carrier in the insulator.[8] Also provided within the chamber is a vibrating Kelvin probe to monitor the discharge of the sample, and a mercury probe to produce temporary metallization for MIS C-V measurements; the latter provides a sensitive measure of charge storage within the insulator.[9]

Use of the above-described techniques has produced exceptionally clear-cut and reproducible results.[6] Our principal experiments to date have been performed on 530-2600 Å films of SiO_2 thermally grown on silicon substrates, using a corona discharge in low-humidity air at room temperature. Steeply rising current-voltage characteristics are obtained at field strengths of approximately 6×10^6 V/cm for positive corona and approximately 1.3×10^7 V/cm for negative corona. Our results cover a considerably greater range than those of Williams and Woods[5] (whose technique limited them to the discharge mode) but agree with theirs in the overlap range. Current density vs. electric field intensity is independent of film thickness. Substantially identical results are obtained with both p- and n-type silicon substrates. MIS C-V measurements taken with the mercury probe indicate no storage of charge in the insulator after charging by positive corona, but positive charge is observed after transport has

been induced by negative corona at field strengths in excess of 1.1×10^7 V/cm.

The p-n junction technique for determination of the sign of dominant charge carrier[8] indicates for both signs of corona that the principal charge carriers in the SiO_2 are electrons. In addition, the measurements taken with negative corona indicate that each electron entering the silicon from the oxide generates approximately one electron-hole pair before thermalizing to the bottom of the silicon conduction band. Tunneling of the hot-hole member of this pair into the oxide, with subsequent trapping near the interface, is the probable source of the positive charging of the oxide found after application of negative corona.

The vibrating Kelvin-probe technique for measuring surface potential in the discharge mode, by virtue of its sensitivity and great accuracy, has provided an unusually reliable vehicle for studying the tunneling of electrons from the silicon substrate into the SiO_2 after charging of the surface by positive corona. In support of the experimental work, a theoretical study has been made of the tunneling of electrons from space-quantized states in the n-degenerate region in the Si substrate, at the Si-SiO_2 interface, into the insulating film. The results of this study have been prepared as a technical report which will be submitted in the near future.[10]

Systematic studies of film breakdown induced by both positive and negative corona discharges are being continued. Thin films of aluminum oxide, silicon nitride, and their layered composites will be studied in addition to silicon dioxide.

The experiments are being extended to cover a range of temperatures to provide additional evidence regarding the mechanisms of charge injection and transport at high field intensities. First to be investigated here will be an anomalous temperature dependence, reported by Lenzlinger and Snow,[11] of currents in a Si-SiO_2-metal structure, other evidence having indicated that the current was contact-limited by tunneling. This has an important bearing on the interpretation of our own results. The corona technique is particularly well suited

to an investigation of this problem.

The use of gases other than dry air are under investigation.

Corona methods are being combined with UV excitation to produce internal photoemission of carriers from the substrate, and with vacuum-UV excitation to provide hole-electron pairs in the insulator. Previous internal-photoemission experiments have relied on the use of a semitransparent metallic field plate to provide the required electric field in the insulator. A photoinjection of holes from the substrate can be accompanied by a simultaneous photoinjection of electrons from the field plate, with possible recombination of the two species within the insulator. All past efforts to photoinject holes from Si into SiO_2 have failed, presumably for this region. Whereas a metallic field plate must have a thickness of more than 100Å to insure integrity of the film, the corona method requires only about one one-hundredth of a monolayer of ions to produce a breakdown field in the insulator; thus photoinjection from the front surface should be minimal. Our first effort in this direction will be to photoinject holes from Si into SiO_2 for a study of hole mobility and trapping in the latter material.

A recent study in our laboratory has indicated that injection of either electrons or holes can be accomplished into silicon nitride by use of a structure like that used in the MNOS memory transistor.[12] We plan to use this process in combination with corona charging to study the high-field transport of electrons and holes in silicon nitride.

(2) Self-Quenched Breakdown of Insulating Films (D. Y. Yang collaborating)

Locally destructive breakdown, isolated and self quenched by local vaporization of the thin metallization near the site of the breakdown,[13,14] has now been used to study Au-Al_2O_3-Si and Al-SiO_2-Si structures, where the Al_2O_3 is pyrolytically deposited and the SiO_2 thermally grown. A result common to both structures is an order-of-magnitude difference in the time scales for breakdown between those situations where the Si substrate is in accumulation at the interface (tens of nanoseconds) and where the substrate is in inversion (hundreds of nanoseconds).

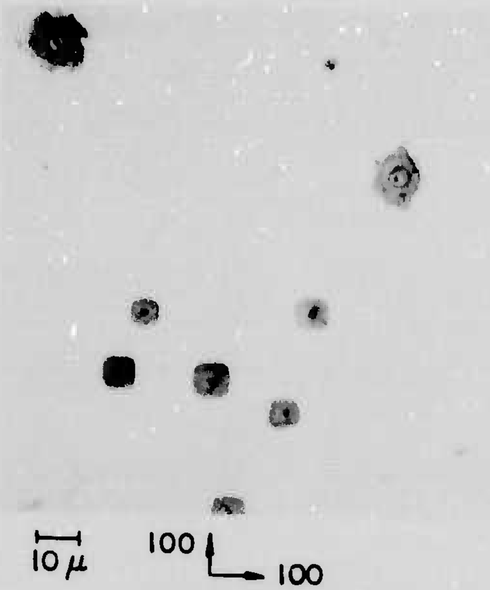
The corresponding equivalent resistances in the discharge path are roughly one hundred ohms (Si in accumulation) and a few kilohms (Si in inversion). In the case of Al_2O_3, at high fields at pre-breakdown, positive gate (Au) voltage charges the film negatively and negative gate voltage charges the film positively, as determined by C-V measurements. These results are consistent with breakdown always initiated at the silicon interface. The results for SiO_2 are the opposite: at high fields at pre-breakdown, positive gate (Al) voltage charges the film positively (up to $10^{17}/cm^3$ volume density of charge) and negative gate voltage produces relatively little charging (C-V flat-band shift less than 5 volts). These results are consistent with breakdown always initiated at the Al interface. Electrons are not strongly trapped in a clean SiO_2 film and therefore do not charge the film, whereas holes are always strongly trapped at the $Si-SiO_2$ interface and therefore charge the film. With positive gate bias the breakdown was sensitive to scratches on the gate; with negative gate bias it was insensitive.

We have used optical and scanning-electron-microscope micrography to record the physical features of the local breakdown sites in SiO_2 which had been thermally grown on silicon and provided with a thin (~ 1000 Å) aluminum field plate. There are four possibilities in regard to substrate conductivity type and field-plate polarity: p- or n-substrate, and simultaneously positive or negative field-plate polarity. Particularly striking are the results that we have obtained at liquid nitrogen temperature with a (100) crystallographic orientation of the silicon substrate. For one (and only one) of the four possibilities mentioned above, namely with a p-type substrate and a positive field-plate polarity, the outer boundaries of the breakdown regions are approximately square with the sides parallel to the (100) crystal axes. This is illustrated in Fig. 1(a), which is an optical photomicrograph of a set of self-quenched breakdowns that were induced at liquid nitrogen temperature, in vacuum, using a p-type substrate. The upper two breakdown patterns were produced by negative field-plate voltage, and are irregular in outline. The lower six breakdowns were

produced by a positive field-plate voltage and exhibit the striking almost-square outline. Shown in Fig. 1(b) are a set of breakdowns induced at room temperature, where the effect is still visible but is less easily seen. Preliminary results using a (111) oriented substrate show no similar phenomenon.

Although the most striking self-quenched boundary configuration is the "square" one associated with the (100) p-type substrate in inversion, each of the other combinations of substrate type and polarity shows its own distinctive pattern of breakdown damage, as can be seen clearly in the SEM micrographs of Fig. 2. These are micrographs of self-quenched breakdowns, induced in vacuum at liquid nitrogen temperature, of 2500 Å SiO_2 films thermally grown on (100) Si, using 1000 Å aluminum field plates. A positive field-plate polarity results in a smooth outer rim for either conductivity type of the substrate, and a negative field-plate polarity results in a "splashed" appearance of the outer rim. When the substrate is in inversion [Fig. 2(a) and (d)] the time scale for the breakdown is of the order of tenths of μsec, and the diameters of the center holes are about 2 μm. When the substrate is in accumulation [Fig. 2(b) and (c)], the time scale of breakdown is considerably shorter - of the order of 10 nanosec - and the center holes are larger - about 5 μm in diameter. With the field plate positive, breakdowns tend to nucleate at scratches on the field plate; with a negative field plate, scratches have no influence. The effect of a scratch is seen in Fig. 2(c); it is not evident in Fig. 2(a) because that particular field plate was not scratched. Fig. 2(d), of n-Si in inversion, shows multiple breakdowns. This is commonly seen with n-Si in inversion and is only rarely seen in the other three combinations. The influence of crystallographic orientation is apparent only in Fig. 2(a).

The anisotropy of the breakdown configuration observed with (100) p-Si in inversion very likely derives from the anisotropy of the hot-electron conduction in Si. Although low-field electron conduction in silicon is isotropic because the components from the



(a) Breakdown at liquid nitrogen temperature

Lower six breakdowns: field plate positive, substrate in inversion. Sides of the "squares" are parallel to the (100) crystallographic axes of the substrate.

Upper two breakdowns (with ragged edges): field plate negative, substrate in accumulation.

(b) Breakdowns at room temperature

Breakdowns with smooth edges (encircled with dashed line): field plate positive; others, field plate negative.

Fig. 1. Optical photomicrographs of self-quenched breakdowns of 2500Å films of SiO_2 thermally grown on p-type silicon with (100) orientation. Field plate is aluminum, thickness 1000Å.

six equivalent conduction-band valleys average out, and hole conduction in silicon is essentially isotropic because of the approximate symmetry of the valence bands about $k = 0$ in reciprocal space, at least two anisotropic properties related to the (100) axes have been observed previously in silicon: hot-carrier excitation has been observed to produce surface breakdown tracks that propagate in the (100) directions,[15 *] and anisotropic hot-electron conduction has been observed in silicon and has been attributed to the multi-valleyed character of the conduction-band structure.[16-18] A giant electrostrictive effect has been observed in n-type germanium and has been linked to the many-valleyed conduction-band configuration of this material.[19] The relationship between these observations and our own remains to be determined. Further work is continuing with different substrate orientations, oxide thicknesses, and metallizations, and a model of the phenomenon is being developed.

(3) Charge-Discharge Studies of Charge-Carrier Trapping in Insulating Films[†] (N. M. Johnson collaborating)

We have designed and constructed apparatus for the convenient exploitation of charge-discharge techniques for the probing of deep traps in thin insulating films, and we have used this equipment and these techniques in a study of the electron traps produced in silicon dioxide by implantation of aluminum and neon ions. The equipment includes a high-vacuum sample chamber, a sample holder arranged for convenient manipulation from the outside and provided with means for heating and for cooling to liquid nitrogen temperature, a soft X-ray generator for excitation of the insulator to produce hole-electron pairs, a high-intensity monochromator arranged for internal photoemission of carriers into the insulating film and for photon excitation of trapped carriers, and appropriate electronic instrumentation including provision for exploitation of the MIS measurement techniques for determination of charge storage and density of interface states.

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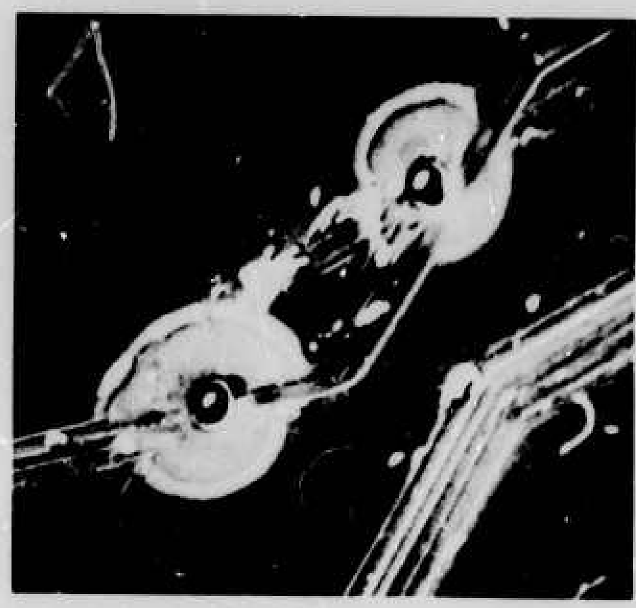
* We are indebted to W. M. Bullis and A. G. Lieberman of the National Bureau of Standards for calling our attention to Reference 15.

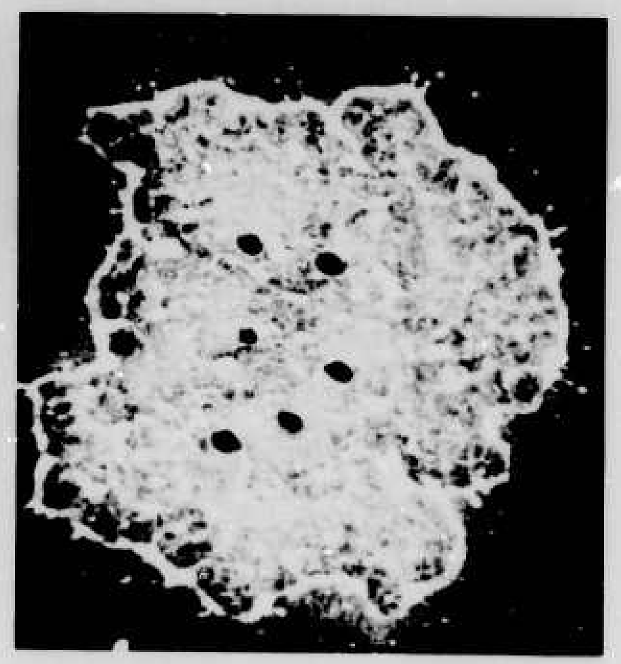
† This work was also supported in part by NRL under ONR Contract N00014-67-A-0151-0030.

(a) p-Si substrate, field plate positive. (x 5000)

(b) p-Si substrate, field plate negative. (x 5000)



(c) n-Si substrate, field plate positive. The breakdowns nucleated at a scratch on the field plate. (x 2000)



(d) Multiple breakdowns with n-Si substrate, field plate negative. (x 1500)

Fig. 2 SEM micrographs of self-quenched breakdowns at liquid nitrogen temperature. SiO_2 thermally grown on (100) silicon, thickness ≈ 2500Å. Field plate is aluminum, thickness ≈ 1000Å .

The wide variety of trap-probing techniques made conveniently available by this equipment will be used as an important adjunct in the other experimental studies.

The study of electron traps in ion-implanted SiO_2 films originated from the observation that ion implantation can improve the radiation hardness of MOS structures under positive gate bias[20-22] and from a speculation that the improvement is caused by increased electron trapping which balances the effect of the strong hole trapping that is always present.[23,24] Our samples consisted of SiO_2 films thermally grown on (100) silicon substrates, as follows: (a) 1400Å thickness, implanted with 20 keV Al ions to a fluence of 10^{14} cm^{-2} and initially unannealed, together with unimplanted control samples, and (b) 4700Å thickness, one set of samples implanted with Al ions and another with Ne ions, implantation energy 10 keV, fluence 10^{15} cm^{-2}, initially unannealed, together with control samples. Semitransparent metallic field plates were vacuum deposited on the exposed SiO_2 surface. Charging of the electron traps in the oxide was accomplished by internal photoemission of electrons from the silicon substrate: a positive voltage was impressed on the field plate and the sample was exposed to 4.8 eV photons from a high-intensity monochromator, this energy being sufficient to raise electrons from the silicon valence band above the barrier to the conduction band of the oxide. During the charging of the traps the sample current was monitored, and at intervals the photoemission was interrupted for C-V determination (at 1 MHz) of the flat-band voltage to indicate the time evolution of the charge stored in the traps. The traps could be discharged either by exposure of the sample to UV light with the contacts short circuited or by thermal annealing at temperatures below 350°C, after which the experiment could be repeated with reproducible results. Data were taken in the foregoing manner over a range of field-plate voltages, stopping just short of anticipated breakdown of the sample. In agreement with previously reported results,[25,26] the unimplanted samples showed little electron trapping. In order to provide a basis for analysis of the results obtained with the implanted samples, the electric-field

dependence of the internal photoemission was calibrated using the unimplanted samples.

The results of this study, which will be detailed in a forthcoming technical report,[27] can be stated briefly as follows: Both the unannealed Al-implanted and the unannealed Ne-implanted SiO_2 films possess large concentrations of deep electron traps that are not present in the normal oxide. Essentially every photoemitted electron was trapped in the more deeply and lightly implanted samples (Al, 20 keV, 10^{14} cm^{-2}) and the dynamics of the electron-trapping process have been successfully modeled. In the more shallowly and heavily implanted samples (Al or Ne, 10 keV, 10^{15} cm^{-2}), the accumulated negative space charge is unstable, possibly indicating hopping conduction between impurity states; this is under investigation. A 600°C anneal for one-half hour is found to reduce substantially the concentration of electron traps. This, together with the large concentration of electron traps found in unannealed Ne-implanted samples, indicates that a substantial fraction of the electron traps are associated with displacement damage in the oxide.

(4) Charge Injection by Electron Beam* (C. T. Shih collaborating)

It is well known that if a suitable contact can be provided to an insulator, the characteristics of the resulting one-carrier I-V characteristic can serve as a powerful probe of the trap structure.[28] We use an electron beam in the 1-5 kV range to inject electrons through a thin metallization and under the surface of a thin insulating film to provide a quasi-ohmic contact to the film. The silicon substrate, biased positively, serves as the anode. The beam, throughout its range in the insulator, additionally produces hole-electron pairs and photons. The steady-state I-V characteristic shows a square-law portion that is independent of temperature but which is linearly proportional to the magnitude of the beam current. Furthermore, the current is considerably smaller than the Mott-Gurney value.[28] This is interpreted in terms of electron trapping in equilibrium with

* This work was also supported in part by NRL under ONR Contract N00014-67-A-0151-0030.

photon detrapping, the photons being those produced by the incident electron beam in stopping. The electron traps required in this interpretation must be bulk traps, not interface traps, and the concentration required is considerably in excess of that found in normal films of thermally grown SiO_2.

In order to obtain independent evidence regarding the foregoing interpretation we have conducted charge-discharge studies of electron trapping, both before and after electron-beam irradiation of the samples, using the apparatus and techniques described in Section II(3). For samples not previously irradiated with the electron beam, an internal photoemission of electrons from the silicon substrate, using 5 eV photons and a positive field-plate polarity, produces only a small amount of electron trapping (0.5 volt flatband shift with 4700 Å film of SiO_2). Subsequent irradiation of the samples with an electron beam at 2.5 kV produces a flatband shift in the positive direction, indicating the storage of negative charge, which saturates at approximately 25 volts. The charge storage is stable over long periods of time but can be partially annealed at 300°C for one hour. The traps remain, however, and can be recharged from photoinjected electrons, whereupon the original flatband shift is restored. These results provide direct evidence of the generation of deep electron traps in thermally grown SiO_2 films by a nonpenetrating (1-5 kV) electron beam.

Relatively few other studies have been made utilizing non-penetrating electron beams[29,30] and these have reported only positive charge storage, near the Si-SiO_2 interface, following the irradiation. A major goal of our current study of this problem is the reconciliation of these earlier results with our own, and we are proceeding on a further investigation of this matter, including the effects of electron beam energy and of fluence.

(5) Scanning Electron Microscope Studies (D. C. Guterman collaborating)

The scanning electron microscope provides an unparalleled tool for the study of microscopic spatial variations. As was mentioned in

Section II(2), the SEM has proved to be very useful in the study of the physical features of breakdown damage. Moreover, we have developed the use of the SEM as a probe of lateral nonuniformities in the insulator and at the insulator-semiconductor interface. Such nonuniformities undoubtedly play a major role in the breakdown properties of the films. By using the beam-induced-current mode of the SEM, we have been able to distinguish structure at the interface between a 1000Å SiO_2 film and its silicon substrate. In a further study, using a 1400Å SiO_2 film on Si, the beam-induced-current image showed the presence of lateral nonuniformities that were not visible in the images produced by primary or secondary electrons and hence were caused by features which lay below the surface, either in the oxide or at the interface. Further studies are being conducted to determine the nature of the observed structure and the role it plays in the breakdown behavior of the insulator. Techniques are under development for differentiation between structure in the insulator and in the interface structure. Also being studied are the current and charge-storage dependence on beam energy, with a view to modeling the processes of charge storage and transport in the insulator. X-ray spectroscopy is being used to provide information about impurities, and especially about aggregations of impurities in the insulator, at the interface, and in the vicinity of local breakdown areas.

(6) Study of Lateral Nonuniformities in MIS Structures* (N. Gordon and C. C. Chang collaborating)

It has been recognized comparatively recently that lateral nonuniformities can be present in MIS structures to a degree previously unsuspected, and that such nonuniformities can seriously affect the performance of devices and circuits based on the MIS structure. There are two areas of concern in this matter. The first is the influence of lateral nonuniformities on the breakdown of the insulating films.[31] The second is the effect of nonuniformities on the interpretation of measurements; for example, the C-V methods conventionally used for

* This work was supported in part by Bell Telephone Laboratories, Inc.

determination of the density of interface states are now known to give erroneous results when nonuniformities are present.[32] Various methods have been proposed for the detection and characterization of lateral nonuniformities,[33] but at the present time the subject remains in an undeveloped and unsatisfactory state.

The a-c conductance technique shows promise as a means of separating the effects of nonuniformities from those of interface states in the MIS structure, but the published theory[34] omits the effect of minority carriers on the measurements. We have analyzed the effect of minority carriers on the frequency dependence of the conductance, $G(\omega)$, of a uniform MIS structure in depletion and weak inversion and find that the minority carriers broaden the curve of $G(\omega)/\omega$ - under some conditions by as much as a factor of two - compared with the results obtained by considering majority carriers alone. It has been suggested, on purely intuitional grounds, that the area under the G-V characteristic should be insensitive to the presence of lateral nonuniformities and thus should furnish the additional information required to separate the effects of interface states from those originating from lateral nonuniformities. In order to test this speculation we have performed an analysis which takes minority carriers into account. The results show that the lateral transfer of minority carriers across the edge of an abrupt nonuniformity substantially increases the generation of carriers from interface states during one half of the cycle and hence increases the area under the G-V characteristic. The abovementioned speculation has therefore been shown to be incorrect. Our development of the theory is being continued with a view to separation of nonuniformity and interface-state effects. The experimental side of this effort is being carried forward in coordination with our other studies of thin insulating films.

(7) <u>Monte-Carlo Calculations of Hot-Electron Distributions</u>
(S. Baidyaroy collaborating)

We have performed Monte Carlo calculations of hot-electron distributions produced by high electric fields in insulating films.

As was discussed in the First Semiannual Technical Report, we have shown that constant mean-free-path problems with anisotropy can be well simulated by one-dimensional random walks with a single anisotropy parameter: the ratio of forward to back scattering probability, f. The computer-generated results can be represented by the relationship $E_{ave,ss} = K_f (F\lambda)^2/\epsilon_{ph}$, where $E_{ave,ss}$ is the mean energy of the electron emerging from the film, K_f is an f-dependent parameter, F is the electric field intensity in the film, λ is the mean free path, and ϵ_{ph} is the optical phonon energy. In the range $0.1 \leq f \leq 0.8$ we find the approximate relationship $K_f \approx 0.1 \exp 4.22f$.

We have also studied the distribution runaway in situations where the mean free path is energy-dependent and increases with increasing energy. Our results show that some electrons escape from the well behaved part of the distribution (much like Shockley's "lucky" electrons) and, once having escaped to a sufficiently large energy, are almost certain to gain energy monotonically. A single such particle, in a finite bunch of particles, is enough to push the average energy into divergence as the film thickness is taken larger and larger. The problem of "escaping" electrons will be discussed in detail in a forthcoming Technical Report.

(8) Theoretical Modeling of Local Breakdown (Dr. Brian Ridley collaborating)

From April 1 to August 10, 1973, Dr. Brian Ridley, Professor of Physics at the University of Essex, Colchester, England, worked with us on a full-time basis in Princeton on a theoretical study of insulator breakdown mechanisms. A model for electrical breakdown in SiO_2 films has been developed along the following lines: Fowler-Nordheim tunneling of electrons at irregularities along the cathode interface produces a locally high current density and Joule heating. Positive ions bound in the oxide volume are thermally released and drift to the irregularity, where they further enchance the local electric field. The result is positive feedback and thermal runaway. The details of this model will be presented in a Technical Report.

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